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ABSTRACT The proposed cooling system for the muon collider will consist of a 200 meter long line of alternating field straight solenoids interspersed with bent solenoids. The muons are cooled in all directions using a 400 mm long section liquid hydrogen at high field. The muons are accelerated in the forward direction by about 900 mm long, 805 MHz RF cavities in a gradient field that goes from 6 T to -6 T in about 300 mm. The high field section in the channel starts out at an induction of about 2 T in the hydrogen. As the muons proceed down the cooling channel, the induction in the liquid hydrogen section increases to inductions as high as 30 T. The diameter of the liquid hydrogen section starts at 750 mm when the induction is 2 T. As the induction in the cooling section goes up, the diameter of the liquid hydrogen section decreases. When the high field induction is 30 T, the diameter of the liquid hydrogen section is about 80 mm. When the high field solenoid induction is below 8.5 T or 9T, niobium titanium coils are proposed for generating the magnetic field. Above 8.5 T or 9 T to about 20 T, graded niobium tin and niobium titanium coils would be used at temperatures down to 1.8 K. Above 20 T, a graded hybrid magnet system is proposed, where the high field magnet section (above 20 T) is either a conventional water cooled coil section or a water cooled Bitter type coil. Two types of superconducting coils have been studied. They include; epoxy impregnated intrinsically stable coils, and cable in conduit conductor (CICC) coils with helium in the conduit.

1. INTRODUCTION

There are two key elements that must work in order for a muon collider to be viable for doing high energy physics research. These elements are: 1) the system that captures pions produced by the collision of an intense proton beam onto a target and 2) the system that cools the muons (by reducing their transverse momentum) that decay from the pions that are produced and then captured (Palmer et al (1998) and Fernow and Gallardo (1995)). Both systems require high field superconducting solenoids so the processes are efficient enough so that the muon don't decay first. This report discusses the parameters of the solenoid that are involved in the muon cooling process.

For a muon collider, the phase-space volume must be reduced within a time that is less than a muon lifetime (2.1 microseconds for a muon at rest). Cooling by synchrotron radiation, stochastic cooling and electron cooling are slow and difficult. Ionization cooling of muons seems to be relatively straight forward. In ionization cooling, the muon beam loses both transverse and longitudinal momentum as it passes through a material medium. Longitudinal momentum is restored when the muon are reaccelerated by RF cavities. If the muon scattering can be limited as it passes through the material medium, there will be a net loss in transverse momentum (net cooling).

A reduction of normalized transverse emittance of three orders of magnitude (from 10^{-2} to $5x10^{-5}$ m-rad) and a reduction of longitudinal emittance is required to do the muon cooling needed for a collider. This can be done by a series of stages that have the following two components: 1) A material in a strong focusing region (low beta perpendicular) alternated with linac accelerators will cooling in transverse phase space. 2) A lattice that generates dispersion with absorbing wedges will introduce and interchange of longitudinal and transverse emmittance. High field solenoids are an integral part of the transverse cooling system.

2. COMMENTS ON THE SOLENOID DESIGN

The basic cooling cell consists of a section with a 400 mm long liquid hydrogen absorber to reduce the momentum of 160 MeV/c muon beam by about 25 MeV/c. There is an RF acceleration section that reaccelerates the muon beam back up to a momentum of 160 MeV/c. A schematic representation of a typical muon cooling section for reducing the transverse momentum of the muons is shown in Figure 1 below.

At the beginning of the 250 to 300 meter long cooling channel the fields at the hydrogen absorbers are rather low and the RF frequency needed to keep the muons in phase is also rather low. As the muons proceed down the cooling channel, both the field at the hydrogen absorber and the RF frequency increases. The diameter of the active region of hydrogen absorber goes down as the inverse of the field that produces the low beta pinch point. The diameter of the RF cavity goes down with frequency and the cavity length needed to add 25 MeV/c to the momentum goes down as one over the square root of the RF frequency.

Table 1 shows the value of the various dimensions in Fig. 1 as a function of the magnetic field in the center of the hydrogen absorber. The cells where the induction in the hydrogen is 2 T are very close to the end of the phase rotation channel. The cells where the induction is above 20 T are at the end of the cooling channel. The cell length at the beginning of the channel approaches 5.2 meters. The cells where the magnetic induction in the hydrogen is above about 12 T will be about 1.54 meters long. In all cases, the field within the RF cavity reverses so that one cell can be matched to the next over a range of muon momenta. The dimensions given in Table 1 are approximate. Further study of the magnet and RF systems are needed to determine the dimensions more precisely.

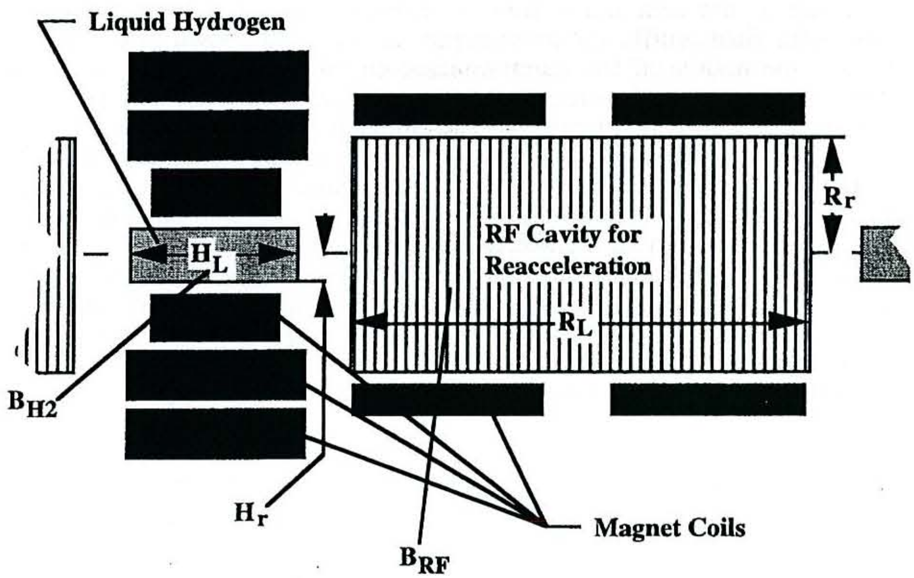

Figure 1 A Schematic Representation of a Typical Muon Cooling Channel Cell

Table 1 Induction Length and Diameter of the Liquid Hydrogen and RF Sections for Sections of an Ionization Muon Cooling Channel for a Muon Collider

H_2 (T)	H_2 Radius H_r (mm)	H_2 Length H_L (mm)	B_{RF} (T)	RF Frequency (MHz)	RF Radius R_r (mm)	RF Length R_L (mm)
2	410	400	2	30	1200	4590
5	180	400	5	200	800	1850
10	100	400	6	400	410	1240
15	70	400	6	805	210	900
20	57.5	400	6	805	210	900
30	45	400	6	805	210	900

Note: The length of a muon cooling cell is H_L plus R_L plus about 0.2 m. The inside diameter of the high field solenoid for the hydrogen section is $2H_r$ plus 0.02 m. The inside diameter of the reversed field RF cavity solenoid is $2R_r$ plus 0.02 m.

The magnet shown in Figure 1 has the high field section that creates the low beta pinch in the muon beam while the hydrogen removes transverse and longitudinal momentum. The coils around the RF cavity are at opposite polarity so that the field reverses in the RF cavity. The next cell down the line has the high field solenoid at a polarity that is opposite from the cell on either side. Ideally the field in the hydrogen absorber increases slightly as one goes down the cooling channel so that each cell is different. It is likely that there will be ten or so identical cells. The currents in the high field coils will be adjusted for optimum muon cooling. The high field coils shown in Figure 1 are graded with the outer coil made from Nb-Ti and the inner coils made from A-15 conductors such as niobium tin or niobium titanium tin. In highest field ends of the cooling channel, the innermost coil may be water cooled conventional coils.

The coils around the RF cavity must shape the field so that the muon beam can be kept captured as it goes through the cooling process. Figure 2 shows the field profile for a single cell of a section of the cooling system that has a high field point of about 16 T. The size and shape of the flux reversal coils control the field profile on axis and cause the slight dip in the magnitude of the induction on axis between the high field low beta coils and the flux reversal coils. Coil design studies show that high current density superconducting coils must be used in the flux reversal section if the proper on axis filed profile is to be maintained. Cable in conduit coils can be used for the high field coils but not in the flux reversal section of the cell. As the field in the liquid hydrogen section goes up, the current density in the solenoid producing that field must also go up. The forces between coils in the flux reversal section are very high (several hundred metric tons). This means that these coils will have to be well designed to carry these large longitudinal forces, even though the peak induction in these windings is less than 9 T. It is proposed that the cooling cells could be operated at 1.8 K so that Nb-Ti can be used for the flux reversal coils. These coils are similar to coils described by Green et al.

Figure 3 at the top of the next page shows a cross-section of a typical 16 T muon cooling cell that produces the field profile shown in Figure 2. The cell shown in Figure 3 could be found somewhere near the middle of the muon cooling channel. Successful muon cooling simulations (with a loss of less than 0.16 percent of the muons per cell, including muon decay) have been done using the cell shown in Figure 3. The Solenoid shown in Figure 3 has three important features. They are: 1) The coils in the high field section are graded so that the Nb-Ti coil produces over 7 T and the two inner niobium tin coils produce about 9 T. 2) There is a stainless steel support structure on the outside of the three high field solenoid coils to carry some of the hoop forces. 3) There is an iron ring between the two high current density flux reversal coils. This ring carries about a portion of the magnetic flux flowing between the two coils, which reduces the force pushing the flux reversal coils apart by about 35 percent. A finite element analysis of the coils shown in Figure 3 suggests that the support structure is needed to keep the strain below 0.2 percent in the high field coils. The iron ring between the inflection coils reduces the longitudinal strain in these coils by over one third.

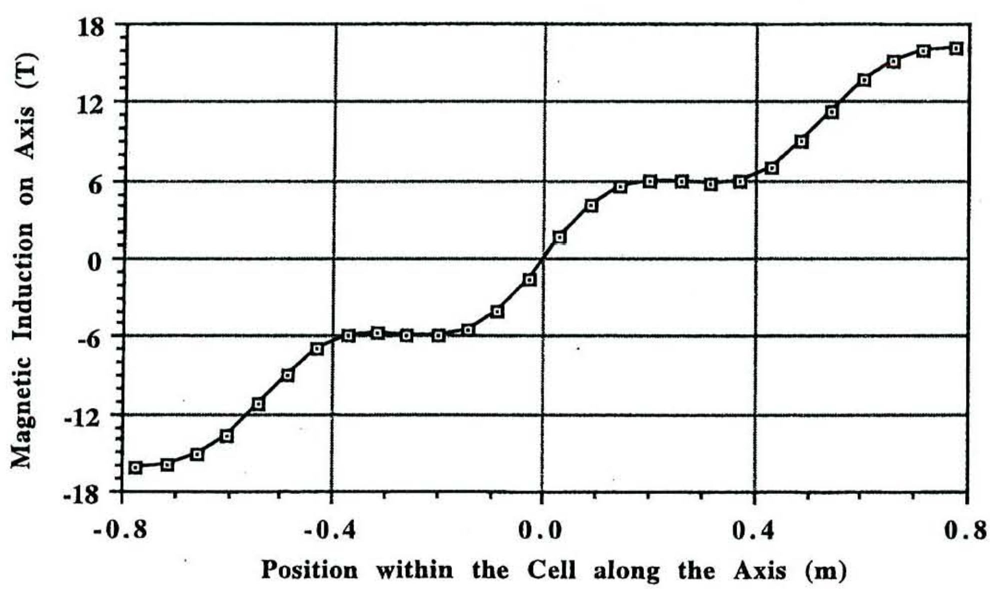

Figure 2 Magnetic Induction on Axis for a Typical Muon Cooling Cell in the Middle of the Cooling Channel

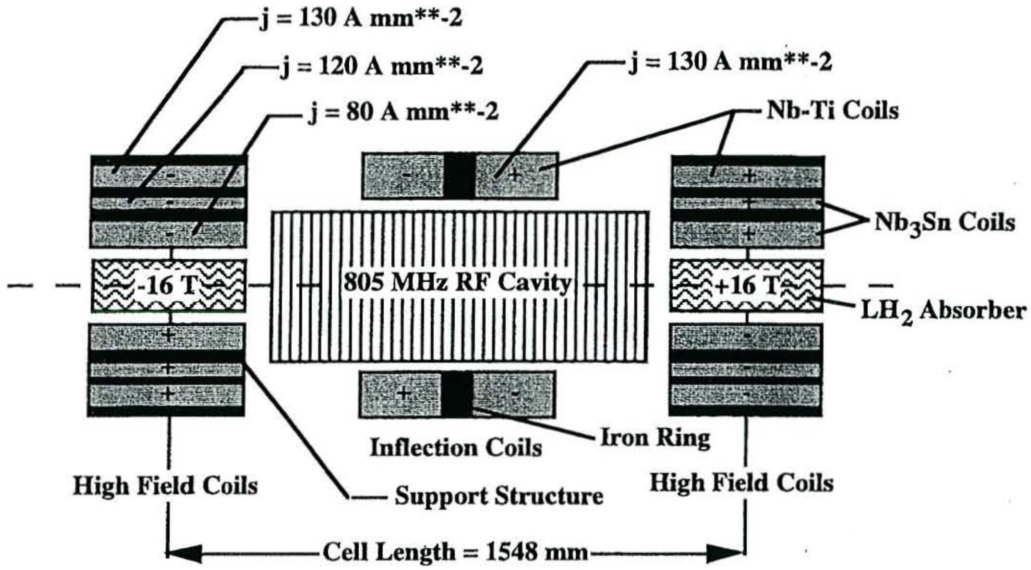

Figure 3 Superconducting Solenoid Cross-section for a 16 T Muon Cooling Cell

3. CONCLUDING COMMENTS

The length of a muon cooling cell will vary depending on where one is in the muon cooling channel. High current density inflection coils are needed in order to achieve the field shape needed to ensure that the muons remain captured during the coiling process. The maximum on axis gradient is above 50 Tm. This means that the inflection coils must be closely spaced. As a result, the force that pushes the inflection coils apart is very high. The addition of an iron ring to soak up some of the flux carried between the coils will reduce the force pushing the coils apart by about a third. Grading the high field solenoid make both economic and technical sense. A stainless steel support structure on the outside of the high field coils will reduce the total strain these coils will see.

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